

## Jet Properties and Evolution in Small and Intermediate Scale Objects

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**Abstract.** Kinematic and spectral studies are improving our knowledge of the age distribution in compact radio sources, providing evidence that small sources are generally very young. The properties of jets in objects spanning the size range from a few tens of parsecs to some kiloparsecs become then of particular interest. Because of our selection criteria and of the small scales involved, the properties of jets in the population of Compact Symmetric Objects (CSO) are not well known yet. Polarization properties seem to indicate a strong influence by the interaction with the dense surrounding medium, and some objects show evidence of relativistic bulk motion. More evolved jets are present in the class of Low Power Compact (LPC) sources and a number of cases are discussed here. Since it is becoming increasingly clear that not all these sources will survive to evolve into large scale radio galaxies, the question of the final evolution of the CSO and LPC population is also discussed, with examples of candidate dying sources.

### 1. Introduction

Despite the large range of resolutions and scales sampled by different radio telescopes and arrays, observations tend to ubiquitously reveal a common basic structure. A central compact core is at the base of two jets flowing in opposite directions, and forming diffuse lobes; bright hot spots can be present at the site of interaction between the jet and the medium confining the lobes. As Fig. 1 shows, this basic structure is found both on sources that are extended over several hundreds kiloparsecs (such as Cygnus A, left image) and in sources that are only a few tens parsecs (e.g. 4C31.04, right picture).

An intriguing explanation of this observational fact consists of a self-similar evolution of radio sources. Radio galaxies begin their life as (sub-)parsec sized objects and then grow up to the kiloparsec scales, making their way through the inter-stellar and inter-galactic medium (ISM and IGM, respectively). In this process, the basic elements are maintained, and their relative weights remain constant.

A number of refinements are required in order to improve over this basic picture, and in particular to overcome the problem of the too large fraction of small sources found in radio catalogs.

1. Not all small looking sources are physically small. Large radio sources, when projected under a small viewing angle, will look rather compact. Because of Doppler beaming, the fraction of such objects is even increased,



Figure 1. Left: Cygnus A, VLA 5 GHz (image courtesy of NRAO/AUI). Right: 4C31.04, Giroletti, VLBA 5 GHz. If brought to the same scale as Cygnus A, 4C31.04 would be only  $\sim 1$  mm wide.

particularly in high frequency catalogs. Unified schemes (see e.g. Urry & Padovani 1995) have been successful in posing a connection between compact and extended sources on the basis of geometry; blazars are a clear example of this.

2. Not all physically small sources grow all the way to Mpc scale; frustration from an over-dense external medium or a lack of fuel for the central engine can be responsible of a premature end of the evolution from small to large scale. While the evidence for frustration has not been found so far, the search for examples of short-lived activity seems to find some support, both on small and intermediate scales (see e.g. Gugliucci et al. 2005; Kunert-Bajraszewska et al. 2005, 2006)
3. The total radio power  $P$  of each object, after an initial increase with radio size, falls as a power law function of linear size  $LS$ :  $P \propto (LS)^{-h}$ . Differently from their compact counterparts, large radio galaxies tend to escape flux limited searches. Models describing different evolutionary tracks are proposed by Begelman (1996); Alexander (2000); Snellen et al. (2000); Tinti & de Zotti (2006).

In the following sections, after some basics about radio source age estimates (§2), we discuss the properties of jets in the case of the smallest radio sources (§3) and of the more evolved low power compact sources (§4). We touch upon the fate of these sources in §5 and give our final remarks in §6.

## 2. Age estimates

### 2.1. Kinematics

A classic way to estimate the age of a source lies in measuring the increase  $\Delta s$  in the separation between its outermost edges over some interval  $\Delta t$ . From these values, one derives a mean advance velocity  $v_{\text{sep}} = \Delta s / \Delta t$  and, assuming that  $v_{\text{sep}}$  has been constant over the source lifetime, the “0-order” estimate of its age as  $t_{\text{kin}} = LS / v_{\text{sep}}$ .

For a reference, let  $v_{\text{sep}} = 0.3c$  and  $z = 0.05$ ; the corresponding  $\Delta s/\Delta t$  is  $0.1 \text{ mas yr}^{-1}$ . Therefore, VLBI observations are the only mean to obtain an estimate of  $t_{\text{kin}}$ . Long time intervals, repeated observations, and high frequency are important element to reveal the motion and make a reliable age estimate.

The first successful report of an increase in hot spot separation was reported in 0710+439 by Owsianik & Conway (1998). Several other studies have reported velocities of  $\sim 0.1 - 0.3c$  in other sources, corresponding to ages in the range  $\sim 10^2 - 10^4 \text{ yr}$  (Polatidis & Conway 2003; Giroletti et al. 2003; Gugliucci et al. 2005).

## 2.2. Spectral ages

Alternatively, one can estimate the age of the source from the study of the high frequency steepening in the spectrum of the emitting particles population. Basic assumptions in the synchrotron theory are as follows:

- a power law initial energy distribution:  $N(E) = N_0 E^{-\delta}$
- radiative losses only:  $dE/dt = -bH^2 E^2$
- a continuous injection of fresh particles:  $Q(t) = NE^{-\delta}$

The observed spectrum is then

$$S(\nu) = \begin{cases} \nu^{-\alpha} & \text{if } \nu < \nu_{\text{br}} \\ \nu^{-(\alpha+0.5)} & \text{if } \nu > \nu_{\text{br}} \end{cases}$$

with  $\alpha = (\delta+1)/2$  and  $\nu_{\text{br}} \simeq 10^9 \times t_{\text{spec}}^2 \times H^3 \text{ (GHz, yr, mG)}$ . Multifrequency observations constrain  $\nu_{\text{br}}$  and allow us to derive  $t_{\text{spec}}$ , if an estimate of the magnetic field is available (equipartition conditions are typically assumed).

Generally,  $t_{\text{spec}}$  estimates are in the range  $10^3 - 10^4 \text{ yr}$  and they agree quite well with kinematic ones (Murgia et al. 1999; Orienti et al. 2007). However, it is important to be careful both in the assumptions going into the model (equipartition magnetic field, no re-acceleration, synchrotron losses only) and in the observations (integrated spectrum, matched  $(u, v)$  coverage), as discussed also by Nagai et al. at these conference.

## 3. The smallest radio sources

In the *youth scenario*, Compact Symmetric Objects (CSOs) represent the earliest stage of the evolutionary path for radio galaxies. Their defining properties can be outlined as follows:

1. **Size/morphology.** CSOs are typically sub-galactic in size ( $LS < 1 \text{ kpc}$ ); their structure, when resolved with VLBI, is that of either a symmetric double or triple; flux density is usually quite stable
2. **ISM related properties.** Probably because of the dense medium of the region in which they form, CSOs tend to have low degree of polarization and to show relatively high HI absorption

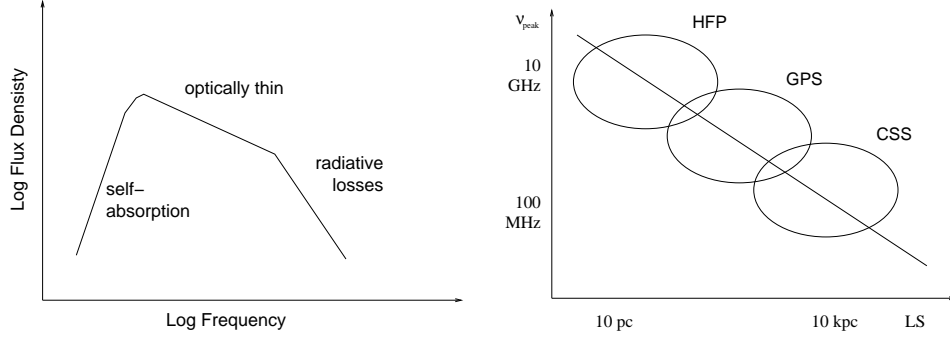


Figure 2. Left: typical synchrotron spectrum; right: the HFP-GPS-CSS sequence in the linear size vs turnover frequency plane.

3. **Radio spectrum.** Their spectrum is typical of synchrotron self-absorbed radiation, i.e. convex with a power-law at high frequency and a low frequency turnover.

These properties, and in particular the characteristic spectral shape, are often used to improve the efficiency of the selection process (see Fig. 2). Interestingly, an inverse correlation has been found between linear size  $LS$  and turnover frequency  $\nu_{\text{peak}}$  (O’Dea 1998). The smaller the source, the higher the turnover frequency, so that a spectral classification is also in use as follows: Compact Steep Spectrum (CSS) sources, GHz Peaked Spectrum (GPS) sources, and High Frequency Peakers (HFP, Dallacasa 2003), with turnover frequency above 0.1, 1, and 10 GHz respectively. It is also worth reminding that blazar contamination becomes more relevant as the  $\nu_{\text{peak}}$  increases. Variability and parsec scale morphology are then required to distinguish between genuine HFPs and blazars (see Orienti, these proceedings).

### 3.1. Jets in CSOs

Since CSOs are selected on the basis of symmetry in arm length and flux density, we are somehow biased in favor of sources in the plane of the sky. This favors viewing angles  $\theta \sim 90^\circ$ , which causes the Doppler factor  $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$  of relativistic jets to become  $< 1$ . Therefore, relativistic jets in CSOs are typically deamed and thus hard to study. Moreover, the angular scales of CSO jets can only be resolved with VLBI and, as a consequence, our knowledge of CSO jets as a class is still relatively poor. There are however several objects in which collimated jets are clearly detected (e.g. 2353+495, Fig. 3, Owsianik et al. 1999). In general, the properties of the jets are strongly influenced by the interaction with the peculiar medium surrounding these sources.

*Bending.* Sharp bends in the jets are not uncommon and they are likely related to the impact on denser clouds which deflects the jet. In the case of 4C31.04, a “dentist drill” model could also be at work (see right panel of Fig. 3 and Giroletti et al. 2003)

*Proper motion* Multi-epoch observations aimed at studying hot-spot advance can also be fruitful in revealing component motions in the jet. While hot spot

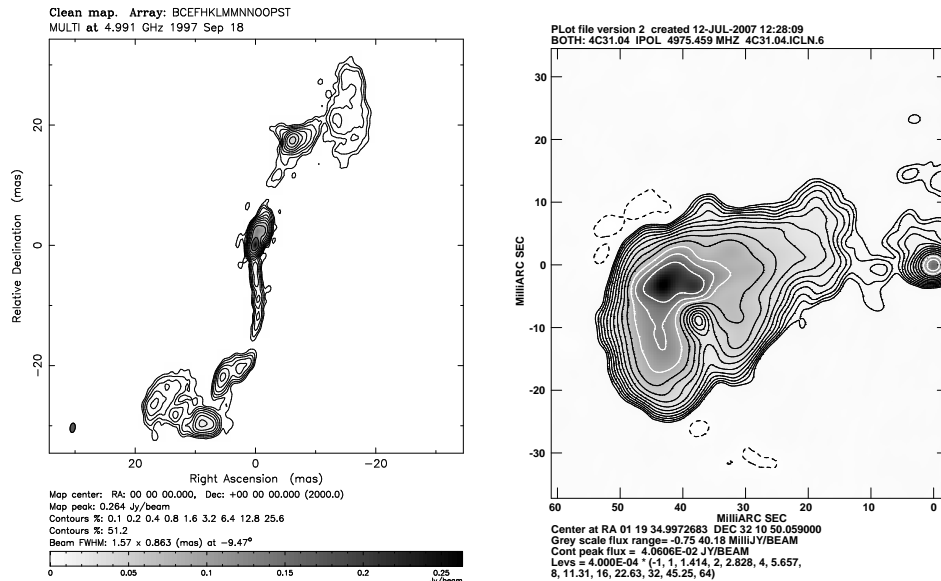


Figure 3. Left: a collimated jet is nicely visible in the 5 GHz image of the CSO 2353+495 (Owsianik et al. 1999). Right: the eastern lobe of 4C31.04, with the sharp bend in the hot spot region, and the remarkable “hole” just next to it.

advance velocities generally do not exceed  $\sim 0.1c - 0.3c$ , jet components can have somehow larger values. Knots in 2353+495 have apparent velocities in the range  $0.3c - 0.8c$  (Taylor et al. 2000), which are quite typical for CSO jets. Subluminal velocities are expected if the viewing angles are close to  $90^\circ$ , as in most CSOs. However, mildly superluminal velocities have been found, e.g. in J1915+6548 (Gugliucci et al. 2007). This source must therefore be more closely aligned to our line of sight, as other properties also suggest (see below). In any case, it seems that CSOs can have relativistic jets ( $\gamma = 5 - 10$ ), once that the advancing hot spots have cleared the densest ISM off the way.

*Polarization* Synchrotron radiation is typically highly polarized. However, because of the Faraday screen constituted by the rich medium around them, CSOs do not usually show polarized flux. Gugliucci et al. (2007) have recently found exceptions to this rule in two CSOs that are less symmetric than the typical CSOs. In particular, the strongest polarization in a CSO jet (9%) has been found in J1826+1831, whose arm length ratio is  $\sim 3$  (see Fig. 4). Interestingly, Gugliucci et al. (2007) also report a Faraday rotation measure as low as  $-180 \pm 10 \text{ rad m}^{-2}$ , which can be attributed to a shorter path length through the circumnuclear torus and, consequently, a lower Faraday depth. Put altogether, this evidence points to a jet closer to on-axis than in other CSOs, just as in J1915+6548 whose jet components are both polarized and (weakly) superluminal.

*High energy emission* Besides the synchrotron radiation, there are other emitting processes that can make CSO detectable in higher energy bands. In par-

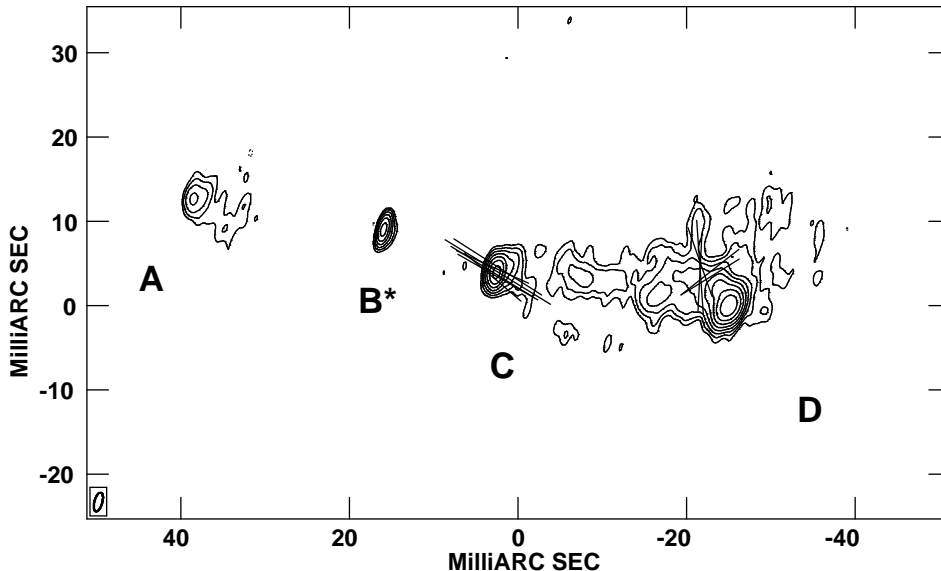


Figure 4. Polarization in the jet of the CSO J1826+1831: fractional polarization of component C is 9%. B\* is the core (from Gugliucci et al. 2007).

ticular, Stawarz et al. (these conference) have suggested that CSOs could be strong  $\gamma$ -ray sources thanks to the IC up-scattering of UV photons from the accretion disk within the radio lobes. It will be intriguing to test this prediction with GLAST.

#### 4. From CSOs to LPCs

On scales of a few kiloparsecs, we find sources that could be evolved CSOs. We name them Low Power Compact sources, and we characterize them by their low radio power ( $P_{\text{LPC}} \lesssim 10^{24} - 10^{25} \text{ W Hz}^{-1}$ ) and linear sizes around a few kpc. Thus, these sources are unresolved in low frequency surveys such as the 3C and the B2, and even in most common VLA configurations. Multiple causes can be invoked to explain the properties of sources in this class: youth, instabilities in the jets, frustration, a premature end of nuclear activity, or just a very low power core (Giroletti et al. 2005b).

Only with observations at high frequency in the A configuration of the VLA, or in phase referencing mode with VLBA, we can resolve LPC sources and discuss their nature. We find rich substructures, including active jets, lobes, and occasionally hot spots. These sources resemble, on an intermediate scale, both the larger classical radio galaxies and the smaller CSOs; however, they tend to be more frequently edge dimmed than higher power sources.

A remarkable LPC source is 0648+27, in which different instruments have been exploited to reveal episodes of activity on different timescales (Giroletti et al. 2005b; Emonts et al. 2006). First off, the radio VLA data at 22 GHz resolve the double source visible at lower frequency, revealing a compact component in the northern lobe (Fig. 5, left panel). Phase referenced 1.6 GHz VLBI data reveal

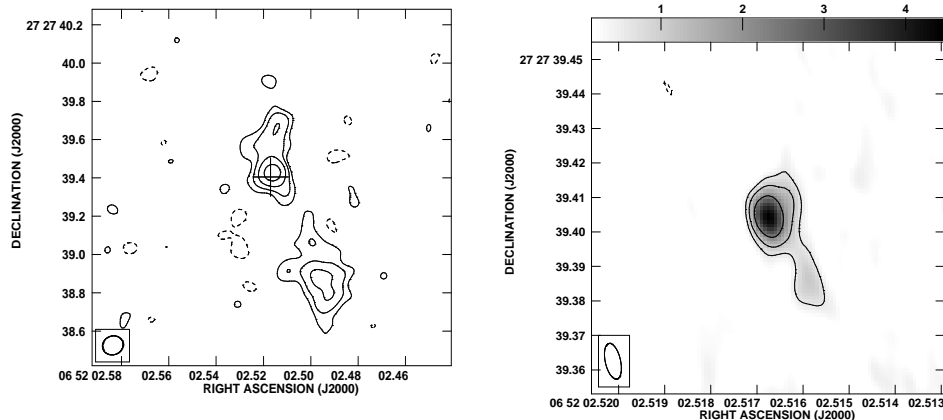


Figure 5. Left: 22 GHz VLA image of 0648+37; the cross denotes the position of the VLBA 1.6 GHz core/jet structure, shown in the right panel.

that this component is actually a flat spectrum core ( $\alpha_{1.6}^{22} = 0.47 \pm 0.03$ ), at the base of a faint jet (Fig. 5, right). The source does not have advancing hot spots and it is not possible to estimate a kinetic age as in typical, young, CSOs. Its larger size fits the LPC definition best, and its spectral age estimate is  $\sim 1$  Myr. Neutral hydrogen 21 cm observations bear also the signature of a major merger occurred  $\sim 1.5$  Gyr ago, while optical spectroscopy suggests an event of starburst activity  $\sim 0.3$  Gyr. Although it is difficult to understand possible connections between the onset of the radio activity and the other events, it is important to gather information across the whole spectrum.

Another interesting source fitting the the LPC definition is NGC 4278 (see Fig. 6, left panel); it has a 5 GHz luminosity of  $\sim 10^{22} \text{ W Hz}^{-1}$ , typical for LLAGNs, and it looks compact on kpc scale. VLBA observations at 5 and 8.4 GHz resolve the source in a flat spectrum core surrounded by two-sided pc scale jets. From a two epochs study, Giroletti et al. (2005a) have revealed a proper motion with sub-relativistic velocity (highest apparent speed  $v = 0.1c$ ), and estimated a Lorentz factor  $1.2 < \Gamma < 1.7$  and a viewing angle of a few degrees.

Several other LPCs have been studied (Giroletti et al. 2005b, and in prep.), revealing cases of jet instabilities, both in space (e.g. in 0222+36) and time (as in 0258+35). In general, high resolution, multi frequency radio observations seem to be successful in understanding the properties of the jets of LPC sources, which are typically  $< 1$  kpc long, often two-sided, and feed “mini”-lobes, rarely embedding hot spots. These jets seem to be in mildly relativistic regime; on the other hand, the mean advance velocity  $v_{\text{mean}}$  of the radio source, obtained by the simple ratio between the linear size and the spectral age ( $v_{\text{mean}} = LS/t_{\text{spec}}$ ), is typically  $v_{\text{mean}} \ll c$ .

## 5. The fate of LPC sources

The low value of the inferred advance velocities raises the question of the possible future evolution of LPC sources. While only a fraction of them seems capable of

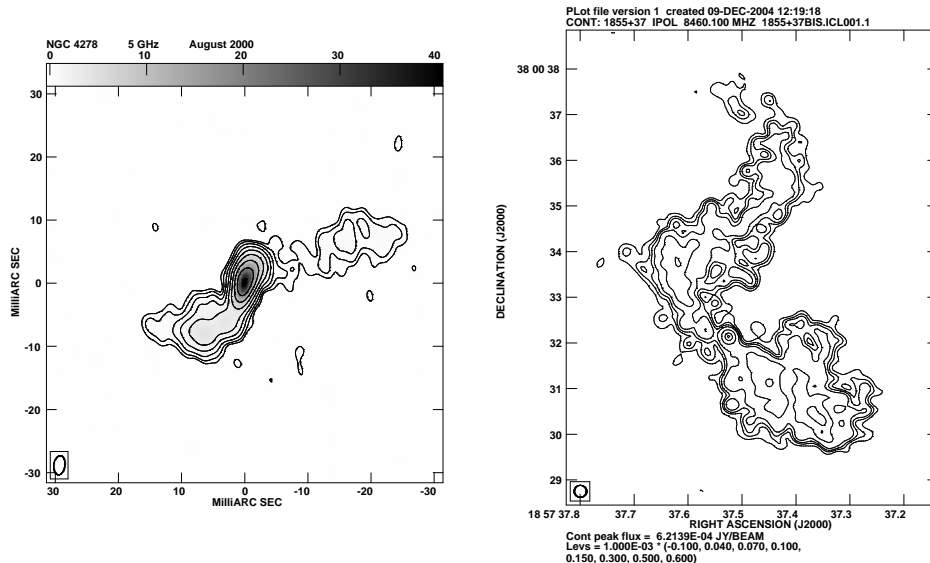


Figure 6. Left: a 5 GHz VLBA image of the two sided parsec scale structure of the LLAGN NGC4278 (Giroletti et al. 2005a). Right: 8.4 GHz image of the head-tail LPC 1855+37, a good candidate of a dying radio source (Giroletti et al. 2005b).

advancing further, and eventually form a large scale FRI or FRII radio galaxy, many of these sources seem unable to form large kpc scale lobes and they will thus face a different destiny. Intermittent activity of the central engine is a possibility, as suggested by the large scale emission found around some pc scale CSO (see e.g. Jamrozy et al., these conference). A premature end of activity can take place in other sources, which are however difficult to find, since  $\nu_{br}$  goes down very rapidly after the injection of fresh particles stops. Only in denser media, e.g. in an X-ray emitting cluster, the fossil phase could last long enough to facilitate our search (Murgia et al. 2005).

An LPC that could be a good example of dying radio source is 1855+37 (Giroletti et al. 2005b). The source has significant extended emission at low frequency ( $S_{408} = 600$  mJy) and is resolved in a nice head-tail at 8.4 GHz (Fig. 6, right panel). However, the VLA core is much weaker than expected ( $S_C = 0.6$  mJy), even if we account for a strong Doppler de-beaming, and it is not detected with VLBA at 1.6 GHz, suggesting that the nuclear activity might be going off. Moreover, the whole source is also not detected at  $\nu > 8.4$  GHz, which could be due to the lack of fresh electrons in the lobes. Finally, the source is in cluster, which could have prevented it from fading too rapidly and escaping detection even at low frequency.

Low frequency observations are particularly important to discover dying sources. Parma et al. (2007) have extracted LPCs with very steep spectra ( $\alpha_{0.33}^{1.4} > 1.3$ ) from a cross correlation of the WENSS and the NVSS surveys. Follow-up VLA multi-frequency observations have confirmed that a number of them could be dying and/or restarted sources.



## 6. Conclusions

The study of extragalactic jets is still posing a number of unanswered questions (e.g. Blandford, this conference). Small and intermediate scale objects can help to answer some important ones. In particular, they can be relevant in the following issues:

- CSOs are the ideal targets to look for jets first steps, and they can be exploited to investigate the reasons of the onset of the radio activity.
- CSO jets strongly interact with the surrounding dense medium and can help to understand its properties, as shown by their significant bends and strong de-polarization. However, because of our current selection criteria, which gives rise to Doppler de-beaming, and of their intrinsic compactness, jets in CSOs are still difficult to study.
- LPCs have more evolved jets, probably relativistic, but not always capable of forming 100's kiloparsecs lobes. The reasons of this fact are not well understood yet but they could be related to the process of accretion on the central super massive black hole.
- A premature end of the nuclear activity is among the possible explanations invoked for the above fact. Though usually difficult to discover, dying or restarted compact radio sources are interesting targets of recent observations.

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